METALLURGICAL CONSULTING
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Metallurgical Analysis
Corrosion
Welding
SEM
Failure Analysis
Fracture Mechanics

RESUME

C. Kendall Clarke, Ph.D., P.E.

President

Metallurgical Consulting

EDUCATION:

Doctor of Philosophy, Metallurgy and Materials Science, Lehigh University, Bethlehem, Pennsylvania, 1973. ñA Fractographic Study of a Low Nickel Steelò

Techniques were developed for utilizing the newly developed scanning electron microscope in critical studies of fracture surfaces. Results were compared with earlier transmission electron microscope work. Fracture mechanics and fracture testing were also involved.

Master of Science, Metallurgy and Materials Science, Lehigh University, Bethlehem, Pennsylvania, 1970. ñThe Kinetics of Manganese Oxide Reduction from Blast Furnace Type Slags by Carbon Saturated Iron.ò

Research and academic programs were conducted jointly in the Metallurgical and Chemical Engineering Departments. Thesis covered experimental and analytical studies of the rate of reaction of a molten slag-metal system.

Bachelor of Science, Metallurgical Engineering, University of Alabama, Tuscaloosa, Alabama, 1968.
Tau Beta Pi honorary.

PROFESSIONAL REGISTRATION

State of Alabama Professional Engineer #15088

State of Mississippi Professional Engineer #18136

WORK EXPERIENCE

April 1977 to Present:

President of Metallurgical Consulting, Inc. (sole proprietorship since 1999). This company provides consulting services in the areas of metallurgy and materials, corrosion, welding, fracture mechanics, and failure analysis. Clients have been in shipbuilding, paper, chemicals, power generation, aircraft, insurance, and law firms. A breakdown of the experience in each of these areas follows:

Metallurgy and Materials

Materials theory and laboratory procedures have been used to solve a wide variety of problems in many metals and in non metal systems. Metals and non metals have been evaluated for deterioration, defects, estimates of temperature exposure and property estimates. Many evaluations have been made on the extent and type of cracking. The extent of heat treatment and probable properties in steels has been determined using optical and electron microscopy. Knowledge of materials behavior has been used to evaluate process equipment for fitness for continued service, set up NDT inspection programs, and to form the basis of fatigue life predictions. Materials studied have included a wide range of steels, alloy steels, stainless steels, high temperature alloys, aluminum alloys, copper alloys, cast irons, fiber glass, graphite, PVC, and elastomers.

Corrosion Analysis

A large number of corrosion problems in metals and non metals have been investigated in high temperature processes, fluid process streams, and cooling water. Potentiodynamic corrosion tests have been used on many of the problems both in the laboratory and on sites. Several projects in process streams and cooling water have involved bacteriological evaluations. Potentiodynamic testing has been used to determine causes of failure, validate corrective actions and predict future rates of corrosion. Electrochemical Impedance Spectroscopy (EIS) has been used to study vinyl and are sprayed coatings.

Welding

Metallurgical principles have been applied to a number of welding areas. Welding problems have been evaluated in both production and repair applications and in steel and aluminum alloys. NDT inspection programs have been established for production and repair welding. Weld procedures have been recommended for repair of process equipment. Welding drawings and procedures have been reviewed for conformance to codes. Numerous spot weld evaluations have been conducted. Set up quality program for welding and high strength bolting on an auditorium project. Developed procedure to analyze substandard fillet welds in complex loading.

Fracture Mechanics

Fracture mechanics has been used extensively to estimate stress levels at failure and in operation in many different components. This analysis procedure has also been used for redesign to insure that cracks can be readily detected before they become critical. Several designs have been evaluated for fatigue using crack propagation or cumulative damage techniques. The approaches of linear elastic fracture mechanics, tearing instability, and ideal plasticity have been used for the appropriate materials.

Failure Analysis

The above areas of expertise have been used where appropriate to evaluate failures in a wide variety of equipment operating under differing conditions. Mechanical failures have frequently involved use of the technique of comparing stress analysis results with stress estimates based on fracture surface studies. Corrosion failure analyses have often involved confirmatory potentiodynamic corrosion testing. Full scale tests have been used to collect data on axle assemblies, doors, and brake systems. Acoustical emission tests have been run on fiberglass door systems. Equipment failures have included many small mechanical components, numerous process

equipment failures, and several large industrial failures. Failure analyses have been conducted in a wide range of metals and non metals.

Large Projects

The following projects are specifically highlighted because of the scope of the work or its complexity. Most of these projects involved extensive testing or analysis or both.

a) Failure analysis of paper mill continuous digester failure involved extensive metallographic analysis, stress analysis and fracture mechanics analysis. Final estimates of pressure at fracture utilized tearing instability theory.

b) Analysis of deareated water storage tank rupture involved metallographic, stress, and fracture mechanics analyses. Directed finite element analysis revealed a significant thermal stress role. The accident sequence was reconstructed based on the analytical work done and a review of plant records.

c) An ammonia storage tank rupture was evaluated primarily with fractography, stress analysis and ideal plastic slip line theory. The accident sequence and failure stress was determined from this work and plant operation history.

d) A fatigue life prediction program was developed for gray cast iron valve bodies over loaded by remotely controlled valve actuators in nuclear plants.

e) A ship board steam line system with improper weld filler metal was analyzed for long term operational performance. Work required extrapolation of high temperature properties and knowledge of ASME code requirements. A successful code case was made that the lines were safe for long term service.

f) A ship board structural weld cracking problem was evaluated by measuring fatigue striation spacing with an electron microscope and estimating operating stress levels. A change from welded to bolted design was recommended and implemented.

g) Fitness for continued service on an old Yankee dryer drum with low shell thickness was determined by estimating cast iron properties using hardness measurements and non destructive metallographic procedures. A finite element analysis provided the basis for rating the vessel for fatigue life.

h) A recovery boiler found to be severely over heated was evaluated through numerous metallographic samples and short term elevated temperature tests of tube samples. A successful case was made to allow continued normal use of the boiler in light of the engineering data.

i) Corrosion in aluminum pipe jackets at Redstone Arsenal was studied in a long term project with the Corps of Engineers. This work involved determining the corrosion mechanism utilizing a specially developed corrosion cell for potentiodynamic testing. Tests were conducted on the lines themselves to identify the moisture source and evaluate alternative jacket materials.

j) A special inline tubular potentiodynamic corrosion cell was developed for side stream evaluation of ferric sulfate corrosion inhibitor in a once through river water heat exchanger with copper:nickel tubes. It was determined that pitting corrosion could be reduced with lower than published rates of ferric sulfate inhibitor additions. The work was published.

k) Two cast iron water line projects were evaluated for corrosion for the Corps of Engineers. One project in the Republic of Panama involved analysis of an existing line for corrosion damage and possible approaches to mitigation. The other involved recommendations for utilizing a non cathodic

protected ductile iron pipeline in north Alabama. Concrete and plastic materials were also evaluated for performance and availability.

l) A production lot of large, high strength steel castings for a US Navy vessel was rejected based on extensive metallographic and mechanical tests. The type of actual heat treatment given was deduced from the testing results. The rejected lot of castings had been quenched but not tempered. The expected service performance of these castings already in service on several navy ships was estimated. The work involved developing a fracture control plan with which to evaluate the materials. Probable toughness of the materials was estimated from casting data. Finite element stress analysis, and stress intensity studies of possible defects were performed. Casting sets in service had been tempered and some had acquired extensive service time.

m) A quality control plan was developed and implemented for welding of large jumbo section wide flange beams used to construct a massive roof girder for a large auditorium. The quality program also included monitoring the proper installation of A490 bolts. No repairs or or rework problems were encountered in the large project.

n) New chlorine heat exchangers started leaking at seal welds shortly after being placed in service. Lack of proper tube rolling was determined by tube ID measurements, ease of driving tubes out of the tube sheet, and by sectioning tube sheets. A dummy block was made and proper tube rolling procedures determined.

o) Tube to tube sheet leaks developed in replacement tube sheets in a SO_2 heat exchanger in a sulfuric acid plant. Initial efforts were directed towards trying to rework the seal welds. This effort failed because of contamination of both from tube installation and erratic tube rolling.

p) Type 310 furnace tubes were failing rapidly in a tree bark burning furnace. An identically built and operated furnace had much longer life. A visit to the furnace operation revealed potential problems and differences in the furnace. The tubes were failing as a result of runaway sulfidation and oxidation at temperatures in excess of 1900 °F. Proposed reasons for the higher sulfur loading and higher temperatures in the furnace were provided. Recommendations to improve the furnace operation were give.

q) A large coating study was performed for the US Army Corps of Engineers to determine a replacement coating for vinyl coatings used on locks and dams. Electrochemical impedance spectroscopy tests on the vinyl coatings revealed rapid water absorption. The zinc rich vinyl primer failed to yield a protective potential. Arc sprayed Zn-15%Al coatings were found to offer better long term life.

r) One out of six nominally identical exhaust stacks on diesel generator on a Navy ship was cracking badly. An extensive scanning electron microscopy evaluation of the fractures eliminated welding as a cause. Fatigue striation measurements and fracture mechanics produced stress estimates three orders of magnitude greater than design. Additional tests revealed that two turbo chargers were out of sync and setting up harmonic vibrations. The combination of out of sync blowers and an oval shaped stack was found to account for high harmonically produced stresses.

September 1976 to May 1977:

Associate professor in Mechanical Engineering, University of South Alabama, Mobile, Alabama. Developed and taught two materials courses. First course provided fundamentals, and the second involved industrial metallurgy. Taught one course each on manufacturing processes and fluid dynamics. Taught two-part course on strength of materials.

June 1973 to September 1976:

Boeing Wichita Division, Wichita, Kansas. Worked in the Metals and Materials Technology Unit and the Commercial Stress Unit. Primary duties were setting up and running the scanning electron microscope, development of new failure analysis techniques, and serving as an in-house consultant on failure analysis and fatigue crack growth calculations. Specific accomplishments were as follows:

1. Principal investigator on NASA contract to study crack growth phenomena. Results published in Engineering Fracture Mechanics.
2. Authored successful proposal on large crack growth study for Air Force. Proposal required a complete review of all written literature on crack growth.
3. Principal investigator on determination of crack growth rate in seawater of Navy developed titanium alloy.

PERSONAL

- Born April 11, 1945 in Ray, Arizona.
- Married to former Carolyn Daniels of Bay Minette, Alabama.
- Active member of Dauphin Way United Methodist Church.
- Member of Official Board Dauphin Way United Methodist Church.
- Past President of Mobile Kiwanis Club.
- Past Lt. Governor Alabama District of Kiwanis International.
- State Convention Chairman for Alabama District Kiwanis 2001 convention.
- Past member of Board of Directors Mobile Symphony and Mobile Ballet.

SOCIETIES

*Alabama and National Societies for Professional Engineers
*National Association Corrosion Engineers
*American Society for Metals
*Society of Automotive Engineers
*American Society for Testing and Materials

PAPERS PRESENTED

1. ñFractography and SEM Artifacts,: ASTM Spring Meeting, Williamsburg, Virginia, 1973.
2. ñCrack Tip Microfracture Processes,ò AIME Spring Meeting, , Pittsburgh, Pennsylvania, 1974.
3. ñBasic Fracture Mechanics.ò ASM-SESA Seminar on Fracture Mechanics, Wichita, Kansas, 1975.
4. ñWork in Crack Growth at Boeing,: SESA Seminar, Kansas City, Missouri, 1975.
5. Numerous talks on failure analysis and fracture mechanics for professional societies and Air Force Laboratories.
6. ñStructural Reliability in Marine Structures,: Society of Naval Architects, Biloxi, Mississippi, September, 1978.
7. ñOverview of Fatigue and Fracture in Naval Ships,ò Fall 1985 Meeting, The Society of Naval Architects and Engineers, Mobile, Alabama, September, 1985.

PAPERS PUBLISHED

1. ñStudy of Crack Tip Closure Using Electric Potential and Compliance techniques,ò Engineering Fracture Mechanics , 1977.
2. ñStudies of Crack Tips in Steel and Aluminum,ò 4th International Conference on Fracture, 1977.
3. ñDegradation of Germanium IR Windows,ò St. Louis IRIS Symposium, 1976.
4. ñThe Economics of Corrosion Control,ò AIPE 1980 Symposium, September 1980, Orlando, Florida.

5. ñAnalysis of a Failed Saw Arbor,ò C.K. Clarke, Case Histories Involving Fatigue and Fracture Mechanics, ASTM STP 918, C.M. Hudson and T.P. Rich eds., A.S.T.M., Philadelphia, 1986, pp 336-343.
6. ñRole of Aerobic Bacteria and their Extra Cellular Polymers in the Facilitation of Corrosion: Use of Fourier Transforming Infrared Spectroscopy and Signature Phospholipid Fatty acid Analysis,ò D.C. White, D.E. Nivens, P.D. Nichols, A.T. Mikell, B.D. Kerger, J.M. Henson, G.G. Geesey, and C.K. Clarke, International Conference on Biologically Induced Corrosion, Gaithersburg, MD., June, 1985.
7. ñCorrosion of Steels Induced by Aerobic Bacteria and their Exocellular Polymers,ò D.C. White, D.E. Geesey, and C.K. Clarke, Proceedings of Argentine/USA Conference on Biodeterioration, April, 1985.
8. ñCorrosion and ground Water Pollution,ò C.K. Clarke, D.C. White, Environmental Health Symposium, Water and Wastewater Issues in the North Central Gulf Coast, April, 1986.
9. "Ferrous Sulfate Treatment of Once Through Water for Cu:Ni Tubing," NACE Corrosion 88, March, 1988, paper #24.
10. ñBasic Requirements for Shipping FRP Equipment,ò F. Britt and C.K. Clarke, 12th Biennial Managing Corrosion with Plastics Sym., Baltimore, MD, 1993 pub. By NACE, vol. XI.
11. ñWheel Stud Bolt Failures,ò C. Kendall Clarke, Fastener Technology International, December, 1994.
12. C. Kendall Clarke: ñFailure Analysis of a Pole Gin,ò J. Failure Analysis and Prevention, 2004, vol. 4 #2, pp 63-72
13. CK Clarke and GE Borowski: ñEvaluation of a Leaf Spring Failure,ò J. Failure Analysis & Prevention, 2005, vol.5, #6, pp 54-63
14. CK Clarke and D Halimunanda: ñImperfections in Tree Stand Failures,ò Journal of Failure Analysis and Prevention, 2006, Vol 6, # 2, pp 24-30.
15. CK Clarke: ñEvaluation of Fire Damaged Copper Wire,ò Advanced Materials and Processes, 2006, Vol 164, # 4, pp 37-39.
16. CK Clarke and D. Halimunanda: ñFailure Analysis of Induction Hardened Automotive Axlesò, Journal of Failure Analysis and Prevention, 2008, Vol 8, #4, pp 386-396.